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The Association of the North Atlantic and the Arctic Oscillation on Wind Energy Resource over Europe and its Intermittency

Pascal Kriesche[a,b,*], C. Adam Schlosser[b]

[a]*Ecole polytechnique, Route de Saclay, Palaiseau 91128, France*
[b]*Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge MA 02139, United States*

Abstract

This study focuses on a better understanding of the influences of the North Atlantic and the Arctic Oscillation on wind power resource over Europe. In the case of a change in phase of the oscillations, wind power density can vary by a factor of three in northern Europe, and a similar effect (but opposite in sign) is seen for southern Europe. Similar results are obtained by calculating the energy output of hypothetical wind turbines. In this way, we have identified an interconnection potential between wind farms in northern and southern Europe in order to reduce intermittency at an aggregate scale.

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Keywords: NAO; AO; teleconnection; wind power density; Europe; interconnection; energy output.

1. Introduction

The European wind industry is growing rapidly. Installed capacity has increased from around 13 GW in 2000 to more than 100 GW in 2012, meeting the power needs of 57 million households. That corresponds to 7% of Europe's electricity demand (EWEA [1]). This positive trend will likely continue to increase in the next decade given that the European Union agreed that 20% of the total final energy consumption should come from renewables by 2020. Of course, wind energy already represents more than a fourth of all new EU power capacity installed in the last year and

* Corresponding author. Tel.: +52-55-1706-2185.
E-mail address: pascal.kriesche@polytechnique.org

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is one of the most promising energy resources to fulfill this ambitious objective. Given these great political conditions, the high potential of wind power and the fact that the technology itself is one of the most mature, it should be of primary importance to better understand the variability of the resource, and to provide solutions to lower its intermittency, as well as to balance its variability. Indeed, one of the biggest challenges for power companies is the ability to provide electricity on demand. As soon as wind resource fails, other sources must be available to compensate the shortage. Whereas diurnal and seasonal variability of wind is quite well known, and wind speed can be forecasted days in advance, only a few studies have been conducted on the influences of teleconnections or large-scale climate variability on wind conditions over Europe. A "teleconnection pattern" in a meteorological field may be defined as a spatial structure with two or more distinct and strongly coupled centers of action according to Deser [2]. Understanding year-to-year variability of wind power density will further help to better anticipate potential energy output and consequently to judge more accurately the economic feasibility of commercial wind farm projects. Thus, the purpose of the present study will be to evaluate the association of teleconnections such as the Atlantic Oscillation (AO) and the North Atlantic Oscillation (NAO) on wind power density over Europe. The NAO index measures the normalized pressure difference between a station in the Azores, for instance in Portugal, and one in Iceland, whereas the AO describes the leading Empirical Orthogonal Function of monthly sea level pressure anomalies during winter pole wards of 20° N. The objective is to provide a comprehensive way to understand and to quantify these influences. For instance, in addition to Principal Component Analysis and correlation studies, wind energy output is estimated for all of Europe using three different model wind turbines. Furthermore, solutions to reduce intermittency are proposed.

2. Data and methodology

2.1. Data set

In our studies we focus on Europe from 34°N to 71.5°N latitudes and from 11°E to 41°W longitudes that is from Portugal to the western end of Ukraine. We used the Modern Era Retrospective-Analysis for Research and Applications (MERRA) data to reconstruct the wind field at 80 m. It is a reconstruction of the atmospheric state by assimilating observational data from different platforms into a global model, Rienecker et al. [3]. Conducted at the NASA Center for Climate Simulation, MERRA aims to provide a more accurate data set using the comprehensive suite of satellite-based information for climate and atmospheric research. The present data set has been constructed with GEOS-5 ADAS (version 5.2.0). It has a spatial resolution 1/2° (lat) x 2/3° (long) and a time resolution of an hour, spanning a period over 31 years from 1979 to 2009. We will consider only the cold season from November to March.

2.2. Wind Power Density Computations

As we are considering power generation, it is more accurate to study wind power density (WPD) rather than wind speed (WS). Indeed, the former takes into account air density, a crucial feature to assess potential power that could be harvested. The WPD at each time step can be estimated by the formula:

$$WPD = \frac{1}{2}\rho WS^3 \tag{1}$$

where ρ represents the air density. Assuming that the air density does not differ considerably at these heights through the well-mixed boundary layer, we use the air density at the center of the lowest model layer ρ. Using theory in boundary layer dynamics and a logarithmical wind profile we calculated the wind speed at a height z:

$$WS_z = \frac{u_*}{\kappa}\log\left[\frac{(z-d)}{z_0} - \psi\right] \tag{2}$$

where z_0 is the roughness length of the surface, d the displacement distance, u_* the friction velocity and κ the von Karman constant. ψ is a function that depends on the stability of the boundary layer. For this study, the boundary layer is assumed to be neutrally stable, avoiding thus the additional ψ function. This assumption seems reasonable knowing that, at the high WS at which wind power is harvested, the boundary layer has large wind shear making it approximately neutrally stable. Finally, we obtain for the at a height z:

$$WPD_z = \frac{1}{2}\rho\left\{\frac{u_*}{\kappa}\log\left[\frac{(z-d)}{z_0}-\psi\right]\right\}^3 \tag{3}$$

The MERRA data set provides us with all the necessary data for ρ, u_*, z_0 and d. It is important to note that the data used and the methodology described above has already been used in previous studies, for instance in Gunturu and Schlosser [4].

2.3. Wind Power Output Estimation

The WPD can be used to estimate a theoretical upper bound for the wind power that can be harvested by a wind turbine at a certain location. Unfortunately this metric does not take into account the technical features of the real wind turbine used. If we wish to calculate a more accurate estimate, for instance the energy output of a turbine, we need to consider the WS distribution at the one hand and a power curve of a specific model turbine on the other hand. Table 1 shows the characteristics of the three different wind turbines used.

Table 1. Characteristics of the three wind turbines used, Vestas [5].

Turbine	Product name	Cut-in WS [m/s]	Rated WS [m/s]	Cut-out WS [m/s]	Height [m]	Swept area [m^2]
Model 1	V100-2.0MW	3	12	20	80	7.854
Model 2	V90-3.0MW	3.5	15	25	80	6.362
Model 3	V112-3.3MW	3	13	25	84	9.852

According to Gasch and Twele [6] we can calculate the generated energy by:

$$E = \sum_i E_i = T\sum_i h_i P_i \tag{4}$$

where h_i is the relative frequency of occurrence of a bin of WS_i. Basically, we are interested in the total annual energy output in kWh for each grid point and for each wind turbine model.

3. Results and Discussion

3.1. Principal Component Analysis (PCA) over Europe

PCA reduces the dimensionality of a set of data into vectors of dominating variance, where the first Principal Component (PC) explains the most variance, the second explains the second-most, etc. Fig. 1 shows the coefficients, or eigenvectors, of the first 4 PCs for the cold season with daily averaged WPD data in order to eliminate diurnal cycles. The first PC explains 14% of the variance, the second 10%, and so on. The areas in the maps with similar coefficient values exhibit the pattern captured in that particular PC. Basically, the red areas in the maps are out of phase with the blue areas. The percentage value can be thought of as a measure of importance of that PC.

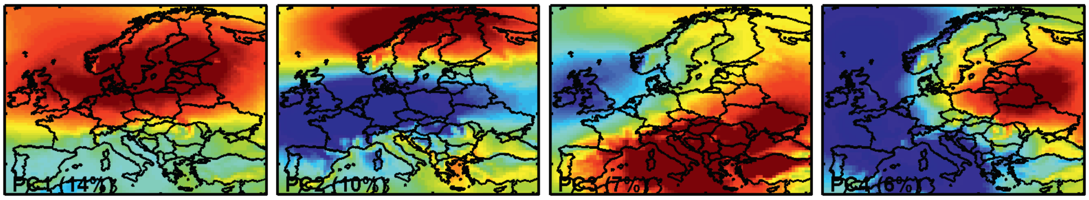

Fig. 1. The first 4 PC coefficients from the PCA of daily WPD. The values in parentheses are the percentage of variance explained by that PC.

In order to increase the relative importance of the variations over land, we decided to use the z-score defined as:

$$z = \frac{x - \mu}{\sigma} \tag{5}$$

where x stands for the data considered, in our case, WPD, μ for its mean and σ for the standard-deviation.

Comparing the time series of the variation of the 50 first PCs with the time series of NAO and AO indices, we found that the first and thus the most important PC is the only one to show great correlations for both NAO and AO. The respective time series for PC1, AO and NAO are shown below in Fig. 2, the correlation seems slightly better for AO than for NAO. All the curves are normalized.

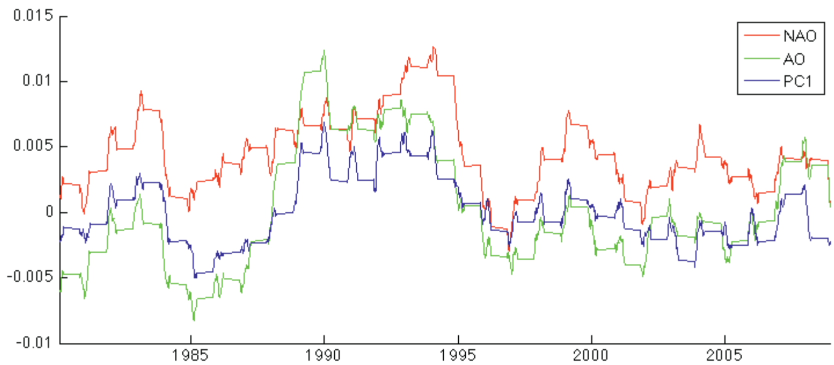

Fig. 2. Normalized time series of PC1 (blue), NAO index (red) and AO index (green) for a running mean of one year.

The cross-correlation sequences between the time series of each of the 50 first PCs of our PCA and the teleconnection indices prove that the highest correlation of 0.46 can be found between PC1 and AO, as well as of 0.32 between PC1 and NAO. Besides, there is no significant lag or lead between the two curves. The maximum correlation is exactly in the middle of the sequence for both teleconnections. Further, we identified a maximum lead of NAO on the variation of PC1 of one day.

3.2. Lead of NAO and AO on WPD

We will try to prove the results of the previous chapter revealing a significant impact of AO and NAO on WPD that had been explained by the first PC accounting for 14% of the total variance of WPD. Therefore we will first look at the correlation between WPD time series and the respective teleconnection index and then give a more comprehensive measure of the impact of these teleconnections.

In order to validate that there is no lag and a maximum lead of one day of the teleconnection on WPD we are studying the cross-correlation sequences between both time series. Fig. 3 shows the histograms of the lags of the cross-correlation coefficient sequence where the highest cross-correlation values can be found for every grid point.

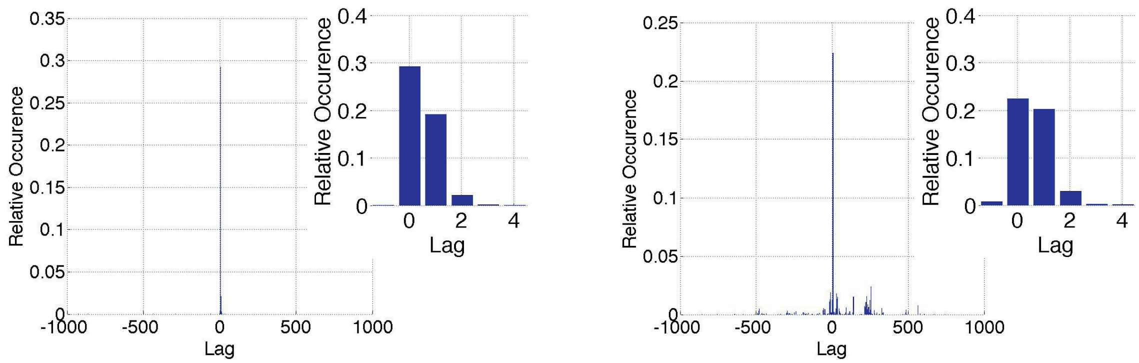

Fig. 3. Histogram of the delay between WPD and AO (left) and NAO (right) for which a maximum correlation can be obtained. Positive x-values correspond to a lead of NAO on WPD, negative ones to a lag (in days). The smaller charts on the right are zooms into the histograms.

In both cases we observe a high peak in the middle around 0 lag. Looking at the histograms in detail we observe that in the case of AO, 29.2% of the grid points obtain their maximum correlation coefficient for a situation without lead or lag of the teleconnection on wind power resource during the cold season (30.5% for the whole data set). Furthermore, 19.1% of the grid points have the maximum correlation at a lead of one day of the teleconnection on WPD (18.4% for the whole data set). In the case of NAO, 22.4% of the grid points have maximized correlation for the situation without lead (15.9% for the whole data set). A lead of one day can be observed for 20.2% of the grid points (15.9% for the whole data set). Two days leads occur in less than 3% of the grid points in both cases. Thus, our results of the cross-correlation analysis of PC1 are proved: 0–1 day lead in the case of AO and NAO. The maximum lead of one day in both cases can be interpreted as a high persistence between AO/NAO and WPD and corresponds to what we could have expected. As a consequence it is important to monitor AO/NAO on a daily basis. Nevertheless, it makes it more difficult to react on AO/NAO changes and to adapt wind power generation for instance. Thus, the prediction of these indices as far in advance as possible becomes an important issue.

3.3. Correlation between NAO/AO and WPD

Not surprisingly the cross-correlation plots for zero and one day lag are almost the same for both AO and NAO, thus we are only presenting the ones in the case of no lag in Fig. 4.

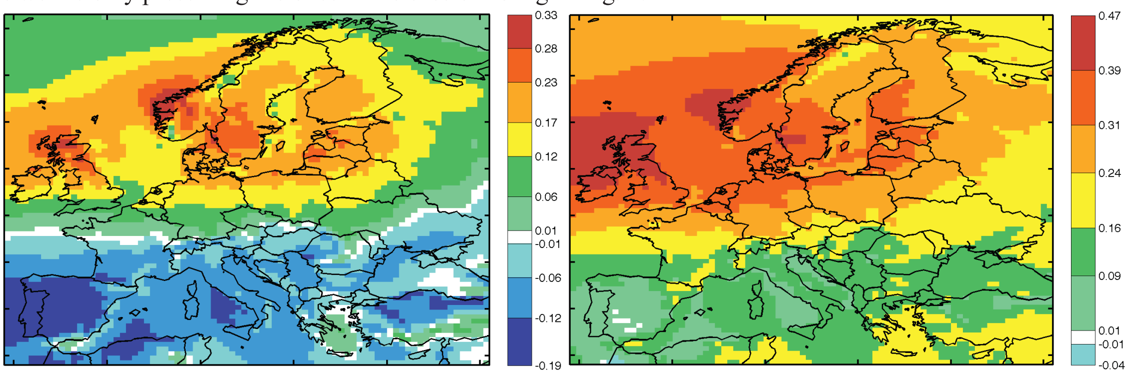

Fig. 4. Geographical variation of the cross-correlation coefficient at a significance level of 1% in the case of AO (left) and NAO (right).

It is important to note that AO and NAO are both highly correlated with WPD for northern Europe, especially northern UK, coastal Norway and southern Sweden, whereas the correlation is much weaker for southern Europe. In the case of AO we observe even a negative correlation for southern Europe. It is highest over Spain. All the plotted correlation coefficients are significant at a confidence level of 99%. These results correspond exactly to what we have seen in PCA, where the eigenvectors of PC1 were best aligned for a large zone in northern Europe. Nevertheless, PCA revealed higher correlation between PC1 and teleconnection for AO than NAO, whereas the correlation between WPD and teleconnection appears to be higher for NAO. If we consider a restriction of the data to the month from January to March the correlations get about 5% higher for both AO and NAO. Taking into account the whole data set on the contrary has the opposite effect and correlations decrease by about 40%. Nevertheless, the geographical variation stays in all data sets qualitatively the same. Smoothing the data used can significantly increase the correlations. For example, for the cold season we obtain correlations up to 0.8 and 0.75 for AO and NAO respectively if we apply a running median of a year to both teleconnection index and WPD.

3.4. Impact of different states of the teleconnection on WPD

Since we can be confident now that a significant correlation exists between AO/NAO and WPD we want to quantify the effect of a changing phase in the teleconnection index in terms of increase or decrease of WPD. As a comprehensive way to do that we chose to divide each teleconnection index into three states: positive, medium and negative. The limits between these states are carefully chosen in order to create bins of equal number of data elements. For each grid point the WPD at a time *t* over the cold season is categorized into one of these three levels depending on the state of the teleconnection at the same time. As a result we obtain a sample of WPD that occur for high or positive NAO/AO as well as one for low or negative NAO/AO. Since we know that there is a maximum lead of one day of teleconnection index on WPD we applied a two-day moving average on the teleconnection time series. In the following we are going to analyze these samples and in particular their relative variations due to a change of the teleconnection phase. Since the histogram of WPD at a certain grid point is highly skewed and a long-tailed distribution, the mean may not faithfully represent the distribution's central tendency of the WPD accurately. As a consequence, we should rather consider the median as presented in Fig. 5.

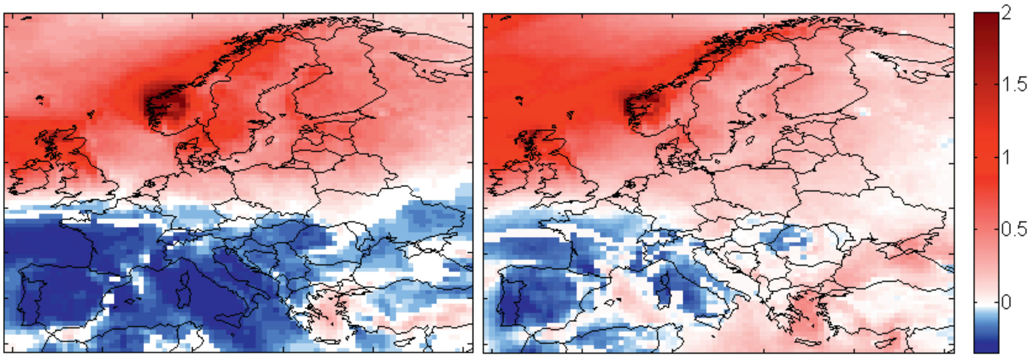

Fig. 5. Relative variation in median WPD at a significance level of 1% if AO (left) / NAO (right) changes from a negative to a positive phase.

Let us first look at the impact of the AO. WPD varies up to 2 times between phases of positive and negative AO. The variations are much stronger for the median than for the mean values. It is important to underline the high confidence level of 99% that has been obtained using a two-tailed t-test for statistical significance. In the case of positive AO, median WPD increases of about 30–200% for north western Europe, whereas southern Europe is characterized by a decrease of about 30-40%. The highest increases can be observed for northern Great Britain and the north west coast of Norway. This different pattern of variation in WPD between the North and the South reveals a high potential for interconnection between wind farms in order to reduce intermittency and to balance the variability of the resource. For instance, in the case of a change of the AO phase from negative to positive the higher amount of generated power by a wind farm located in the North could be used to compensate the lack in wind energy generated by a southern wind farm. If AO turns negative again the opposite will happen and the North can be balanced by the South. In the case of the NAO our results are quite similar to the ones stated above for AO. Nevertheless, regions with decrease of WPD in the South seem to be less widespread and weaker. Besides the area with increase of WPD is more located in the North West. Quantitatively, the increases are slightly lower. Nevertheless, a similar potential for interconnection between wind farms can be noted. Again, Fig. 5 is completely consistent with the areas of similar pattern identified in the first PC in PCA. Since the probability of apparition of each state of AO/NAO equals one third we can further say that this high interconnection potential can be exploited at least two third of the time. Nevertheless, an increase in intensity of WPD due to high AO/NAO is always associated with an increase in standard deviation. Consequently, the WPD distributions get much wider and the risk occurs that only a small percentage of the WPD can be converted to electricity since power curves are only defined for a limited interval of WS.

3.5. Geographical variation in generated energy

Given these limitations we would like to do the same study as before, comparing the impact of different phases of the teleconnections on the real energy output by wind turbines instead of WPD that should rather be considered as a potential upper bound of energy that could be extracted. We will do that for every grid point over Europe. Fig. 6 shows the relative differences in generated energy between positive and negative phases of both AO and NAO for turbine model 3. We identify an important north-south difference confirming the high potential of interconnection between northern and southern Europe that has already been stated before when looking at WPD. It seems to be stronger for AO than for NAO. Effectively, in the case of a positive AO phase, up to 200% more electricity can be generated in the North compared to a negative teleconnection phase whereas the generation in southern Europe decreases by about 40–50%. The plots for the other model wind turbines look really similar. This result is meaningful since it tells us that independently from the wind turbine used there will always be a high potential for interconnection between wind farms between the North and the South.

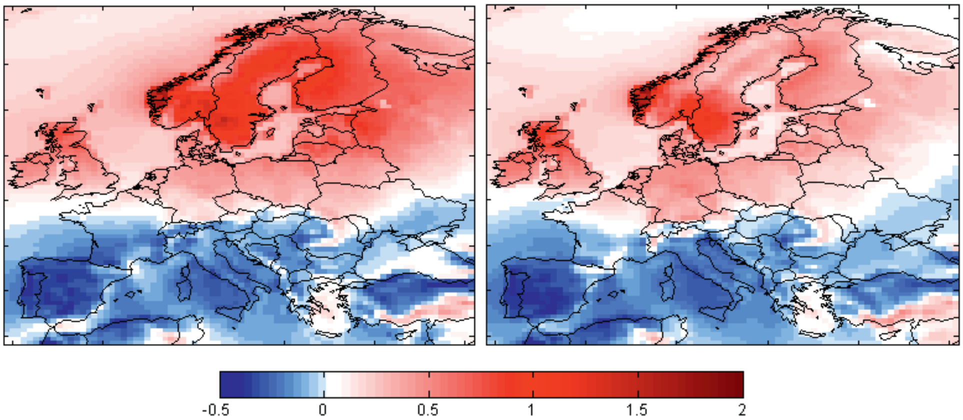

Fig. 6. Relative variation in energy output in the case of turbine 3, if AO (left) or NAO (right) changes from a negative to a positive phase.

4. Conclusion

In the present study the impact of AO and NAO on wind energy resource over Europe have been evaluated and, if possible, quantified. Since much of Europe sees a maximum point-wise temporal correlation with AO/NAO leading WPD by at most one day it is important to monitor AO/NAO on a daily basis. Generally, the correlations between WPD and teleconnection index are slightly higher for NAO. From the PCA analysis we can infer that as much as 14% of the overall variation of WPD over Europe is explained by AO/NAO. Coefficient of determination studies for linear regression between WPD and teleconnection time series confirm this result. For northern Europe up to 30% of the variation of WPD can be explained by NAO, for example. In the case of high AO/NAO, WPD can get up to three times higher in northern Europe compared to a low teleconnection phase. The opposite effect can be observed for southern Europe; WPD decreases here by up to 50%. This different variation due to AO/NAO across Europe reveals a high potential for interconnection between wind farms in order to balance their variability and to reduce intermittency, one of the greatest challenges facing widespread deployment in wind power generation. Our study of the generated energy output using model wind turbines provides a more realistic measure to prove this high interconnection potential, and shows that it is independent from the wind turbine used. Furthermore, predicting AO/NAO, can significantly help wind farm operators adapt to future wind power variations and stabilize wind power output throughout Europe, for example, by providing the right back up technology for lost wind power e.g. in the south of Europe when a positive phase of AO/NAO occurs. As a consequence, taking into account our results, wind power can become a more reliable and less intermittent resource that will help its expansion across Europe.

Compared to studies on the influence of teleconnection on wind resource over Europe that have been conducted before, it is important to note that our study is the first to look at WPD on a large scale. Our study also provides a more comprehensive analysis since we include air density and are thus able to estimate the upper bound of wind power that can be generated independently from the wind turbine used. In addition, we estimated the effective energy output for every grid point over all of Europe for several wind turbines of different scales.

Nevertheless, we should be aware of the limitations of the present study. First of all, the data set has been obtained by assimilation of measurements and satellite remote-sensed data into a global model. The imperfections of the model and the assimilation schemes are accordingly bound to influence the computed output. Due to the spatial resolution of 1/2° x 1/3° some local effects that change WS such as mountain passes and valleys are not represented. In addition, since the teleconnection indices have time resolution of at least one day, intermittency and other phenomena of higher scale and their effects can only be studied.

Our study clearly underlines that the interconnection of the electricity grids over whole Europe should be a priority for the European Union given the potential to balance the teleconnectivity from AO/NAO. A study on the economic feasibility of interconnection of wind farms, and the resulting losses due to the transmission of electrical current, should be conducted. Furthermore, it would be interesting to study the correlations between teleconnection indices and real wind power that has been harvested by wind farm operators using electricity generation data over all of Europe.

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